

Electromagnetic transitions for $A=3$ nuclear systems

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Abstract. Recent advances in the study of pd radiative capture in a wide range of center-of-mass energy below and above deuteron breakup threshold are presented and discussed.

INTRODUCTION

The electromagnetic transitions for $A=3$ nuclear systems have been extensively studied by several research groups (see Ref. [1] for a review). The advantage of investigating these processes is that nowadays several methods can provide accurate bound- and scattering-state wave functions using realistic Hamiltonian models. Therefore, different models for the nuclear electromagnetic current operator can be tested with the large body of available experimental data. In the present study, we concentrate our attention on the pd radiative capture reaction in a wide range of center-of-mass energy ($E_{c.m.}$). This reaction was already studied below the deuteron breakup threshold by our group in Ref. [2], using pair-correlated hyperspherical harmonics (PHH) wave functions obtained from a realistic Hamiltonian model consisting of the Argonne v_{18} two-nucleon [3] and Urbana IX three-nucleon [4] interactions (AV18/UIX). The nuclear electromagnetic current operator included, in addition to the one-body term, also two-body contributions, constructed following the method of Ref. [5], with the goal of satisfying the current conservation relation (CCR) with the AV18. However, within this method, the two-body terms originated from the momentum-dependent part of the AV18 were not strictly conserved. The pd radiative capture observables were all quite well reproduced with the “full” model for the nuclear current operator, with the only exception of the deuteron tensor polarization observables T_{20} and T_{21} . In the analysis of Ref. [2], it was concluded that these discrepancies might be due to the fact that the electromagnetic current operator satisfies the CCR with the nuclear Hamiltonian only approximately.

In this work we present a new model for the nuclear current operator constructed so as to satisfy *exactly* the CCR with the AV18/UIX Hamiltonian model, and we test it in the study of the pd radiative capture observables in a wide range of $E_{c.m.}$. The model for the nuclear electromagnetic current operator is summarized in the following section. A detailed review will be given elsewhere [6].

THE NUCLEAR ELECTROMAGNETIC CURRENT OPERATOR

The nuclear electromagnetic current operator can be written as sum of one- and many-body terms that operate on the nucleon degrees of freedom. The one-body operator is derived from the non-relativistic reduction of the covariant single-nucleon current, by expanding in powers of $1/m$, m being the nucleon mass [1]. To construct the two-body current operator, it is useful to adopt the classification scheme of Ref. [7], and separate the current into model-independent (MI) and model-dependent (MD) parts. The MD two-body current is purely transverse and therefore is un-constrained by the CCR. It is taken to consist of the isoscalar $\rho\pi\gamma$ and isovector $\omega\pi\gamma$ transition currents, as well as the isovector current associated with excitation of intermediate Δ resonances as in Ref. [2]. The MI two-body currents have longitudinal components and have to satisfy the CCR with the two-nucleon interaction. The MI terms arising from the momentum-independent terms of the AV18 two-nucleon interaction have been constructed following the standard procedure of Ref. [5], hereafter quoted as meson-exchange (ME) scheme. It can be shown that these two-body current operators satisfy *exactly* the CCR with the first six operators of the AV18. The two-body currents arising from the spin-orbit components of the AV18 could be constructed using again ME mechanisms [8], but the resulting currents turn out to be not strictly conserved. The same can be said of those currents from the quadratic momentum-dependent components of the AV18, if obtained, as in Ref. [2], by gauging only the momentum operators, but ignoring the implicit momentum dependence which comes through the isospin exchange operator (see below). Since our goal is to construct MI two-body currents which satisfy *exactly* the CCR with the complete AV18 two-nucleon interaction, the currents arising from the momentum-dependent terms of the AV18 interaction have been obtained following the procedure of Ref. [9], which will be quoted as minimal-substitution (MS) scheme. The main idea of this procedure, fully reviewed in Ref. [6], is that the isospin operator $\tau_i \cdot \tau_j$ is formally equivalent to an implicit momentum dependence [9]. In fact, $\tau_i \cdot \tau_j$ can be expressed in terms of the space-exchange operator (P_{ij}) using the formula $\tau_i \cdot \tau_j = -1 - (1 + \sigma_i \cdot \sigma_j)P_{ij}$, valid when operating on antisymmetric wave functions. Note that the operator P_{ij} is defined as $P_{ij} = e^{\mathbf{r}_{ji} \cdot \nabla_i + \mathbf{r}_{ij} \cdot \nabla_j}$, where the ∇ -operators do not act on the vectors $\mathbf{r}_{ij} = \mathbf{r}_i - \mathbf{r}_j = -\mathbf{r}_{ji}$ in the exponential. In the presence of an electromagnetic field, minimal substitution is performed both in the momentum dependent terms of the two-nucleon interaction and in the space-exchange operator P_{ij} . The resulting current operators are then obtained with standard procedures [6, 9]. Explicit formulas can also be found in Ref. [6].

Both the ME and the MS schemes can be generalized to calculate the three-body current operators induced by the three-nucleon interaction (TNI). Here, these three-body currents have been constructed within the ME scheme to satisfy the CCR with the Urbana-IX TNI [4]. Details of the calculation can be found in Ref. [6].

In summary, the present model for the many-body current operators retains the two-body terms obtained within the ME scheme from the momentum-independent part of the AV18, those ones obtained within the MS scheme from the momentum-dependent part of the AV18, the MD terms quoted above, and the three-body terms obtained within the ME scheme from the UIX TNI. Thus, the full current operator satisfies *exactly* the

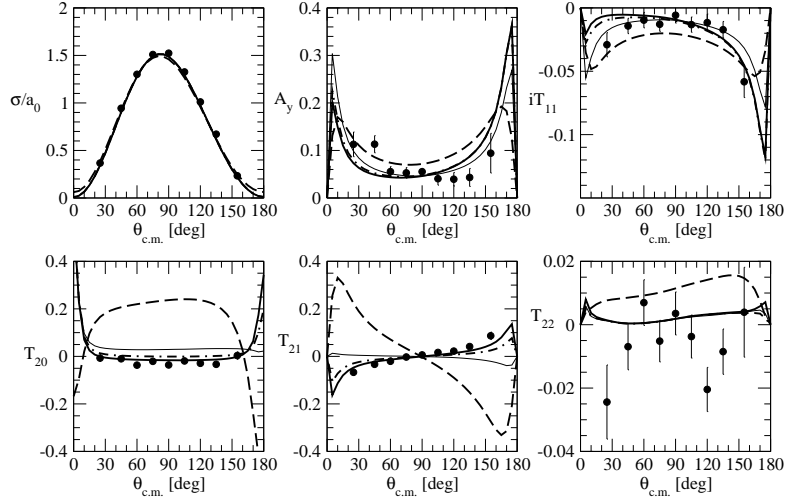


FIGURE 1. Differential cross section, proton vector analyzing power, and the four deuteron tensor polarization observables for pd radiative capture at $E_{c.m.} = 2.00$ MeV, obtained with the AV18/UIX Hamiltonian model. See text for the explanations of the different curves. The experimental data are from Ref. [11].

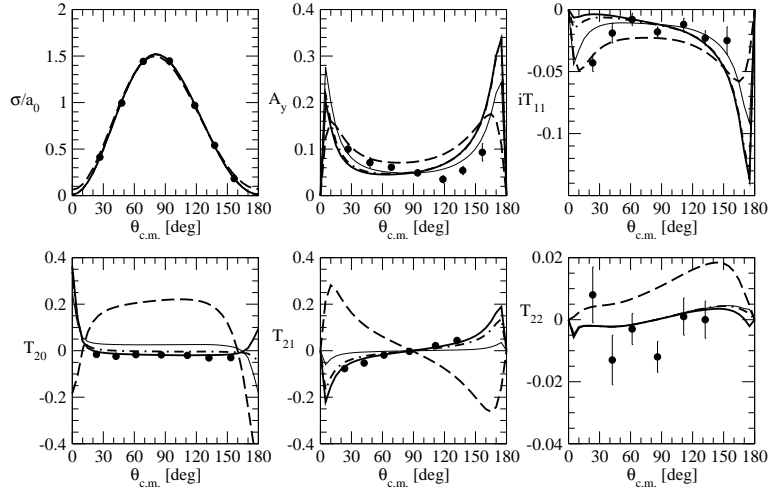


FIGURE 2. Same as Fig. 1, but at $E_{c.m.} = 3.33$ MeV. The experimental data are from Ref. [12].

CCR with the AV18/UIX nuclear Hamiltonian. In contrast, the model of Ref. [2] retains only two-body currents, all of them obtained within the ME scheme.

RESULTS

The theoretical predictions of the pd radiative capture observables at $E_{c.m.} = 2.00$ – 9.86 MeV obtained with the AV18/UIX Hamiltonian model are compared with the available experimental data in Figs. 1–4. In all the figures, the dashed, dotted-dashed and thick-

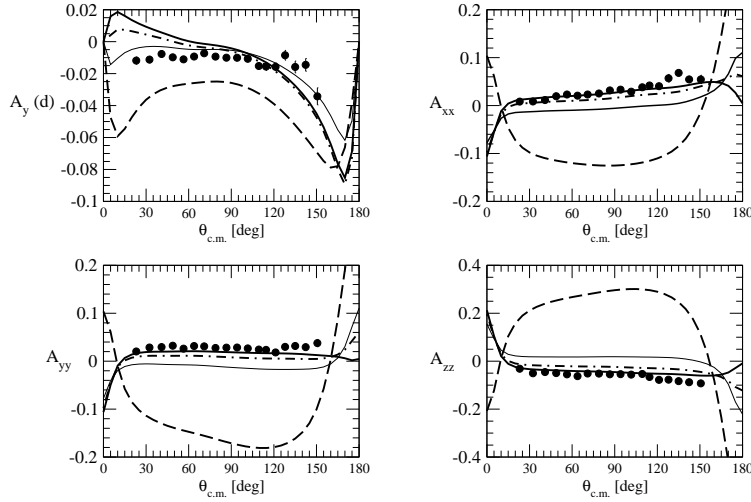


FIGURE 3. Deuteron vector and tensor polarization observables at $E_{c.m.} = 5.83$ MeV. The experimental data are from Ref. [13].

solid curves correspond to the calculation with one-body only, with one- and two-body, and with one-, two- and three-body currents. Also shown (thin-solid lines) are the results obtained with the model for the nuclear current operator of Ref. [2]. From inspection of the figures, we can conclude that: (i) the present “full” model for the nuclear electromagnetic current operator provides an overall nice description for all the observables, with the only exception of the deuteron vector analyzing powers iT_{11} and $A_y(d)$ at small center-of-mass angles. The origin of these discrepancies is currently under investigation. A possible explanation could be a deficiency in the used model for the TNI, in particular in the absence of three-nucleon spin-orbit terms [10]. (ii) Some small three-body current effects are noticeable, especially in the deuteron tensor polarization observables T_{20} , T_{21} at $E_{c.m.} = 2.00$ and 3.33 MeV and A_{xx} , A_{yy} and A_{zz} at $E_{c.m.} = 5.83$ MeV. This is an indication of the fact that if a Hamiltonian model with two- and three-nucleon interactions is used, then the model for the nuclear current operator should include the corresponding two- and three-body contributions. (iii) The results obtained with the model of Ref. [2] are in strong disagreement with the data for the deuteron tensor polarization observables. This is a consequence of the fact that in Ref. [2] the CCR is only approximately satisfied. However, this “old” model seems to provide a better description for the deuteron vector polarization observables iT_{11} and $A_y(d)$.

SUMMARY AND OUTLOOK

We have reported new calculations for pd radiative capture observables in a wide range of $E_{c.m.}$ below and above deuteron breakup threshold. These calculations use accurate bound and scattering state wave functions obtained with the PHH technique from the Argonne v_{18} two-nucleon and Urbana IX three-nucleon interactions. The model for the electromagnetic current operator includes one-, two- and three-body components,

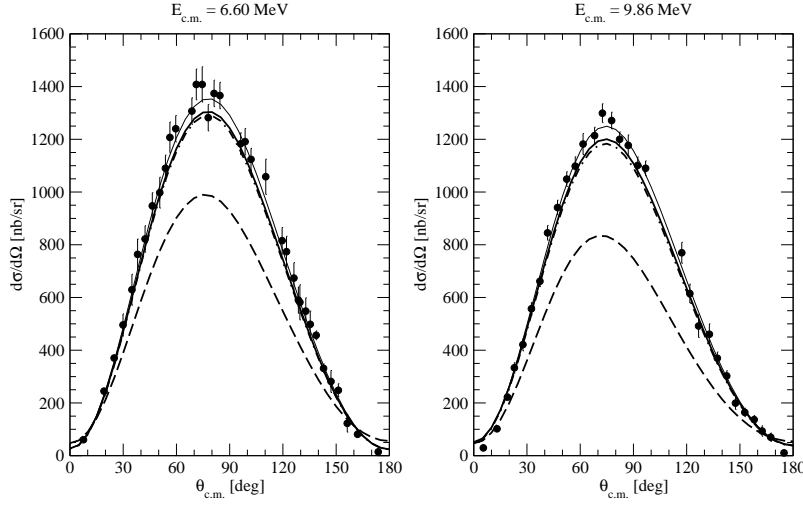


FIGURE 4. Differential cross section for pd radiative capture at $E_{c.m.} = 6.60$ MeV (left panel) and 9.86 MeV (right panel). The experimental data are from Ref. [14].

constructed so as to satisfy *exactly* the CCR with the given Hamiltonian model. An overall nice description of all the observables has been achieved, with the only exception of the deuteron vector analyzing powers at small angles. A systematic comparison between theory and experiment for the pd radiative capture in a wider range of $E_{c.m.}$ is currently underway [6].

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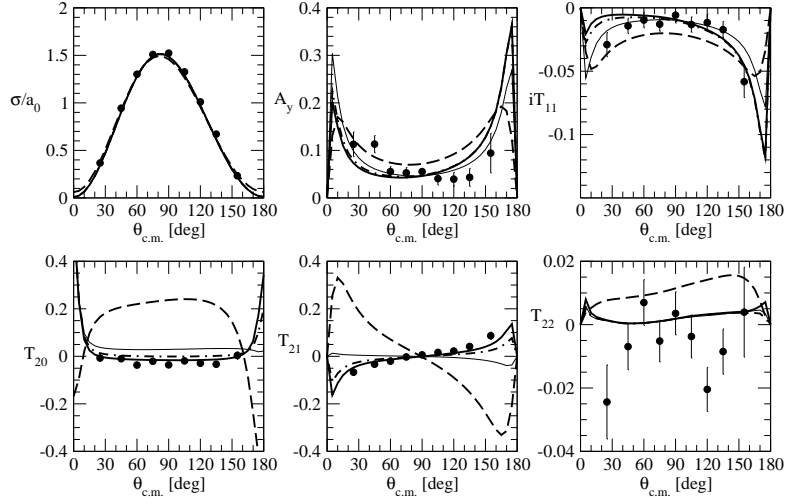


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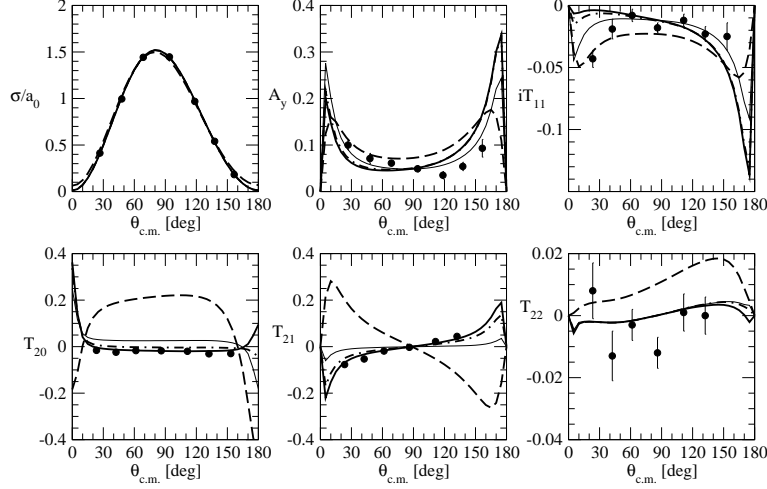


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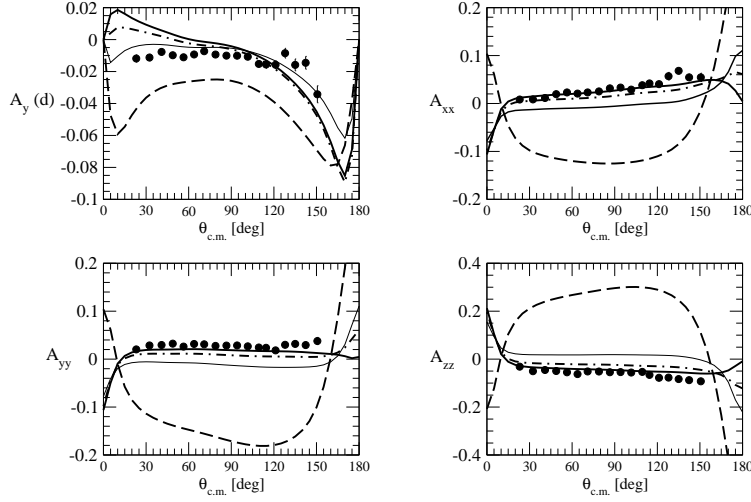


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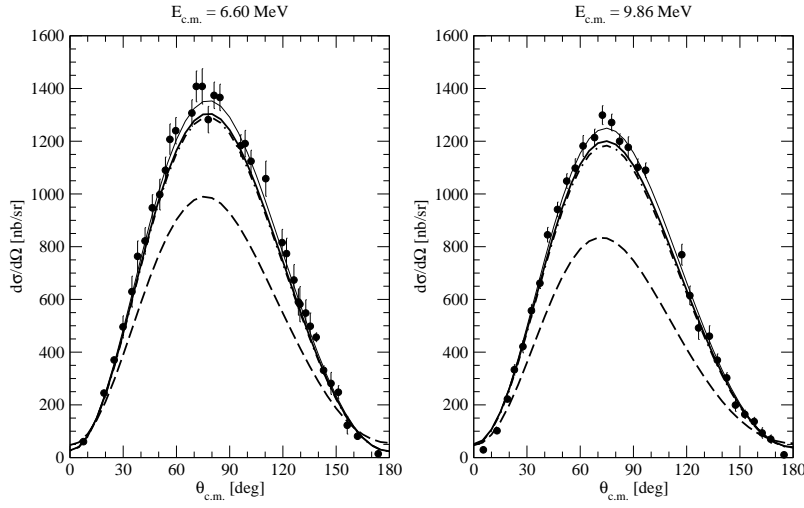


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